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Institutional Computing: Annual Progress Report

Precision early universe simulations to constrain nuclear reactions and beyond standard model physics

Scientific and Programmatic Impact

The current one-year allocation (w20_qburst) is the first year in a two year allocation of the same name. The project has supported two publications [1, 2] in peer-review journals, another manuscript in preparation for publication [3], a white paper for the Astro2020 Decadal Survey [4], and a number of talks (see below). Code development continues on implementing a neutrino quantum kinetic equation solver into BURST, now called QBURST. While implementing coherent and forward-scattering processes into the dynamical neutrino evolution equations, multiple numerical issues have appeared. We have remedied a number of these issues through extensive debugging and testing, which include streamlining interpolation and implementing new ODE integration techniques. Further testing is required to solve the problem at a precision of better than one part in 10^6. We expect that we will understand the numerical difficulties and implement solutions by end of year 2021.

Scientific impact encompasses multiple areas: *i)* time-evolution of neutrino flavor and number density from 10^{-3} to 10^3 seconds in the life of the universe, *ii)* updated nuclear reactions using new experimental results, *iii)* foray into physics beyond the standard model with strongly-interacting neutrinos and dark photons. Multiple advances in numerical abilities include: *i)* a new and streamlined interpolator, *ii)* separate module for neutrino coherent and forward-scattering processes, *iii)* diagonalization of complex matrices using Jacobi algorithm, *iv)* further development of numerical integration algorithm including Runge-Kutta and Predictor-Corrector methods.

Observational cosmology is entering an era where precision will reach 1% for neutrino and nuclear-related observables and parameters. The list of observatories includes, but is not limited to: Cosmic Microwave Background experiments (e.g., CMB Stage IV), thirty-meter class telescopes (e.g., Thirty Meter Telescope, Giant Magellan Telescope, and European Extremely Large Telescope), and deep spectroscopic surveys (e.g., Vera Rubin Observatory). The code QBURST will provide a framework for two separate but related research thrusts: predictions via the standard-model on neutrino-energy parameters and primordial-abundance observables; and characterizations of beyond-standard-model signals for the same parameters and observables. These predictions will be verified/refuted by the future cosmic observatories. Work over the previous allocation has focused on beyond-standard-model physics research thrust, namely by studying strongly self-interacting neutrinos (SIν) and dark-photons.

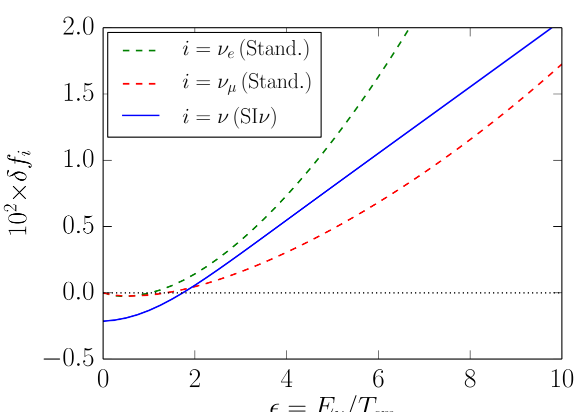

Figure 1: Strongly self-interacting neutrino spectra (blue line) computed via QBURST.

Recently, SIν have been invoked to ameliorate the tension between CMB and local Type-Ia Supernova measurements of the Hubble expansion rate. A neutrino remedy posits an interaction which is 9 orders of magnitude stronger than the weak interaction. Such an interaction leaves the neutrinos coupled to one another well into atomic recombination and could have consequences on BBN. Reference [1] explores these consequences and finds that although the neutrino dynamics are significantly altered (see Fig. 1), primordial abundances and neutrino energy densities are only slightly modified. The conclusion was that BBN is consistent with a SIν cosmology at the level of 1% precision. To explore the parameter space, we ran QBURST with a variety of different physical configurations. The physics of SIν allowed us to describe the neutrino evolution equations using two parameters, namely a temperature and chemical potential. This enabled a vast speed-up in computation time as the interpolator no longer needed to be called. As a result, for the first time we were able to submit a batch job with QBURST where the neutrino transport physics subroutines were included.

We have also studied dark photons in the early universe in Ref. [2]. A variety of dark photon models have been proposed to explain experimental anomalies and also provide a portal to the dark sector and dark matter. We selected a suite of models where the standard-model photon mixes with a massive dark-sector particle which we call a dark photon. For the set of models we picked, we showed that entropy flows out of the electromagnetic plasma and into the dark photon sector at high temperature, and then the reverse process occurs at low temperature. The neutrino distributions track the electromagnetic plasma distributions although the coupling is weaker and hence the effects more subtle. We showed that the neutrino energy density is the parameter most sensitive to this physics, whereas the abundances show very little change. Our simulations with QBURST showed that high-precision cosmological parameter estimation will require an out-of-equilibrium treatment of the neutrino distributions to capture beyond-standard-model physics. If future CMB experiments see a slight decrease in the neutrino energy density and no concomitant change in the primordial abundances, this scenario provides ample evidence for an entropy-changing event similar to the dark-photon models studied in Ref. [2].

Code work continues on the Quantum Kinetic Equation (QKE) implementation in QBURST. Over the previous year, work on the SIν project has facilitated a closer inspection of the interpolator for the neutrino distributions used in the transport subroutines. We have optimized the searching algorithm to find a set of bins to do the interpolation based on a particular binning scheme. In addition, we store the results from the searching algorithm which avoids the need for multiple calls. The new prescription requires minimal additional memory storage but is a vast improvement on time. Finally, we dynamically choose the order of the interpolation on each call instead of fixing the order for all calls to the interpolator. These modification have given us on order a factor of 10 speed up during testing runs. Besides the improvements in interpolation, we have also put all coherent and forward-scattering neutrino processes into a separate module. We designed the module such that each term can be included/excluded so as to test which terms cause spurious noise in our simulations. The results of these tests have shown that the non-linear forward scattering term of neutrinos off of other neutrinos is causing spurious signals in the imaginary components of the generalized neutrino density-matrix distributions. Further work may call for a numerical integration scheme which uses a Magnus method where all of the coherent and forward-process terms are transformed out of the integro-differential equations. This kind of transformation requires a prediction of what the non-linear forward scattering term should be, and further iterative corrections to ensure convergence per time step. We have developed our own predictor-corrector algorithm based on the Adams-Bashforth method where we can implement a Magnus method. However, this algorithm requires the diagonalization of 3x3 matrices and so we wrote a Jacobi diagonalization module to solve the linear algebra problem. The Jacobi procedure can be repeated to arbitrary precision. We do not foresee either a loss of precision or timing when using the Jacobi procedure. Solving the QKE problem in the early universe will produce two letters describing cosmological and neutrino physics results, and a longer paper describing the numerical methods. With a QKE solver, we plan on exploring other problems such as lepton-asymmetries in the neutrino sector, and many-body versus mean-field approaches to neutrino flavor transformation.

Publication List

[1] E. Grohs, George M. Fuller, and Manibrata Sen. Consequences of neutrino self-interactions for weak decoupling and big bang nucleosynthesis. J. Cosmology Astropart. Phys., 2020(7):001, July 2020.

[2] Jung-Tsung Li, George M. Fuller, and Evan Grohs. Probing dark photons in the early universe with big bang nucleosynthesis. J. Cosmology Astropart. Phys., 2020(12):049, December 2020.

[3] Evan Grohs and A.B. Balantekin. Dirac Neutrino Magnetic Moments in the Early Universe. Submitted to Phys. Rev. D, 2021.

[4] Evan Grohs, J. Richard Bond, Ryan J. Cooke, George M. Fuller, Joel Meyers, and Mark W. Paris. Big Bang Nucleosynthesis and Neutrino Cosmology. BAAS, 51(3):412, May 2019.

Selected Talks

E. Grohs (Research Assistant Professor – North Carolina State University)

- February 2019, Primordial Nucleosynthesis and Neutrino Quantum Kinetics in the Early Universe, Astrophysics seminar, Los Alamos, NM
- April 2019, Neutrinos and Weak Interactions in the Early Universe, Nuclei as BSM Laboratories workshop, Trento, Italy
- June 2019, Weak Interactions and Synthesis of the Primordial Elements, P-25 seminar, Los Alamos, NM
- July 2019, Modeling the Neutrino Dynamics of the Early Universe, LANL ICUG meeting, Los Alamos, NM
- August 2019, Big Bang Nucleosynthesis and Neutrino Cosmology, 15th Recontres du Vietnam: Cosmology conference, Quy Nhon, Vietnam
- August 2019, Neutrino Quantum Kinetics in the Early Universe, NBIA-LANL Neutrino Quantum Kinetics in Dense Environments workshop, Copenhagen, Denmark
- September 2019, Neutrino Dynamics in Big Bang Nucleosynthesis, Durham University Astronomy Seminar, Durham, United Kingdom
- September 2019, Neutrino Dynamics in Big Bang Nucleosynthesis, University College London Extraordinary seminar, London, United Kingdom
- September 2019, Neutrino Dynamics in Big Bang Nucleosynthesis, Institut d'Astrophysique de Paris seminar, Paris, France
- September 2019, Neutrino Dynamics in Big Bang Nucleosynthesis, Max Planck Institute for Astrophysics seminar, Garching, Germany
- October 2019, Neutrino Quantum Kinetics in the Early Universe, Topics in Cosmic Neutrino Physics workshop, Batavia, IL
- January 2020, From the Sun to the Cosmos: Solving the Neutrino Flavor Equations, Looking for ν Physics in the Earth and in the Cosmos symposium, Berkeley, CA

- January 2020, Neutrino Quantum Kinetics in the Early Universe, Neutrinos from the Lab to the Cosmos workshop, Seattle, WA
- February 2020, Neutrino Quantum Kinetics in the Early Universe, Theory seminar, St. Louis, MO
- May 2020, Self-Interacting Neutrinos in Big Bang Nucleosynthesis, N3AS Zoom seminar, Virtual
- August 2020, Precision Neutrino and Nuclear Physics in the Early Universe, North Carolina State University Department of Physics colloquium, Virtual

G.M. Fuller (Professor – University of California San Diego)

- August 2019, Neutrino Physics in Cosmology, NBIA-LANL Neutrino Quantum Kinetics in Dense Environments, Copenhagen, Denmark
- October 2019, Neutrino Decoupling, BBN, and High Precision CMB/CνB, Topics in Cosmic Neutrino Physics workshop, Batavia, IL
- January 2020, Neutrino Flavor, Nuclear Physics and Entropy, and the Dark Sector, Looking for ν physics on Earth and the Cosmos symposium, Berkeley, CA
- January 2020, Neutrino Flavor Quantum Kinetics, Entropy, and the Dark Sector, Neutrinos from the Lab to the Cosmos, Seattle, WA

Financial Impact

There are multiple sources of funding for this ongoing HPC-IC project. E. Grohs was initially funded through the Network for Neutrinos, Nuclear Astrophysics, and Symmetries (NSF Grant No. PHY-1630782 and Heising-Simons Grant No. 2017-228). E. Grohs is currently funded through DOE Contract No. DE-FG02-02ER41216 and NSF-supported JINA-CEE at North Carolina State University. G.M. Fuller is funded through NSF Grant No. PHY-1914242 at University of California San Diego. The DOE nuclear theory program at LANL (code E9BF) has benefited from this project.

Prepared by: Evan Grohs